Time-domain observation of strong coupling between ultra-high $Q$ whispering gallery modes

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We report the time-domain observation of strong coupling between two coupled ultra-high $Q$ whispering gallery modes. If two modes couple strongly, the light energy oscillates between them in the time domain. We employed two counter-propagating whispering gallery modes in a silica toroid microcavity for this purpose. The combination of a large coupling coefficient between the clockwise (CW) and counter-clockwise (CCW) modes and their ultra-high $Q$ factor result in a clear energy oscillation in the time domain. Our measurement is based on a drop-port measurement technique, which enables us to observe the light energy in the two modes directly. The period of the energy oscillation precisely matched that inferred from the mode splitting in the frequency domain.

Key words: Silica toroid microcavity; Coupled cavity; Strong coupling; Mode splitting;

1. Introduction

Whispering gallery mode (WGM) microcavities are attractive because they typically have an ultra high $Q$ and a reasonably small $V$ [1]. Thanks to their high $Q/V$ ratio, light can be strongly confined and the light-matter interaction is greatly enhanced in the cavity.

A system incorporating a coupled microcavity system is currently attracting a lot of attention. When the cavities couple strongly, it is well known that the resonance is split in the frequency domain [2]. On the other hand, photons are transferred back and forth between two cavities in the time domain, which leads to energy oscillation. Energy oscillation has already been experimentally observed and controlled in coupled photonic crystal nanocavities with the aim of achieving quantum information processing [3]. However, such experiments have yet to be reported with ultra-high $Q$ WGM cavities despite the potential benefit of using an ultra high-$Q$ microcavity.

In this study, we report the first time-domain observation of energy oscillation between coupled ultra-high $Q$ WGMs [4]. There were two keys to achieving the observation. First, we employed two counter-propagating WGMs with a $Q$ of $> 10^7$ in a silica toroid microcavity. It is known that the part of the light scattered by the surface couples back into a mode propagating in the opposite direction in an ultra-high $Q$ WGM cavity [5]. This induces coupling between clockwise (CW) and counter-clockwise (CCW) propagating modes. By using CW and CCW modes as a platform for the experiment, we can greatly simplify the experimental setup.

In addition, we employed a drop-port measurement technique, where two tapered fibers are brought close to the cavity, to allow us to observe the energy oscillation clearly. When a single tapered fiber is employed, the light coupled into the fiber from the cavity is disturbed by interference with the light transmitted through the fiber. On the other hand, when the drop-port measurement technique is used, we can observe the light coupled from both the CW and CCW modes because there is no transmitted light in the drop-port tapered fiber.

2. Numerical analysis

First, we develop a numerical model to simulate the dynamical behavior of coupled WGMs using coupled mode theory (CMT) [6]. The master equations of the model are as follows (see Fig. 1(a));

$$\frac{d a_{CW}}{dt} = \left( j \omega_0 - \gamma_1 \right) a_{CW} + \frac{\kappa}{2} a_{CCW} + \sqrt{\gamma_{bus}} s_{in},$$  \hspace{0.5cm} (1)

$$\frac{d a_{CCW}}{dt} = \left( j \omega_0 - \gamma_1 \right) a_{CCW} + \frac{\kappa}{2} a_{CW},$$  \hspace{0.5cm} (2)

$$s_{out,t} = s_{in} - \sqrt{\gamma_{bus}} a_{CW},$$  \hspace{0.5cm} (3)

$$s_{out,r} = \sqrt{\gamma_{bus}} a_{CCW},$$  \hspace{0.5cm} (4)

$$s_{out,dl} = \sqrt{\gamma_{bus}} a_{CCW},$$  \hspace{0.5cm} (5)

$$s_{out,dr} = \sqrt{\gamma_{bus}} a_{CW},$$  \hspace{0.5cm} (6)

where $a_{CW}$, $a_{CCW}$, $s_{in}$, $s_{out,t}$, $s_{out,r}$, $s_{out,dl}$, $s_{out,dr}$, $\omega_0$, $\gamma_{bus}$, $\gamma_{drop}$ and $\kappa$ are the cavity mode amplitudes of the CW and CCW modes, the waveguide mode amplitudes at the input, the transmission, the reflection and the drop (left and right) ports, the angular resonant frequency, the coupling rate between the cavity and the tapered bus and drop fibers, and the coupling rate between the CW and CCW modes, respectively. If $\kappa$ is larger than $\gamma$, the cavity resonance is split. Typical split cavity modes are shown in Fig. 1(b). Note that if we employ an
input signal Fourier transform that overlaps well with two peaks (dips) in Fig. 1(b), we are able to excite time-domain energy oscillation between the two modes.

Fig 1 (a) Schematic illustration of developed model. (b) Calculated transmission (blue) and reflection (red) spectra of the cavity with \((\kappa, \gamma_0, \gamma_{bus}, \gamma_{drop})/2\pi = (100, 10, 2.5, 0)\) MHz.

Here, we discuss a method for observing energy oscillation between the CW and CCW modes. In general, we observe a transmission \((s_{\text{out,}\text{t}})\) to characterize a microcavity. However, as can be understood from Eq. (3), the transmission is the product of the interference between lights coupled from the CW mode and transmitted through a tapered fiber. So, the transmission port is not suitable for observing the energy oscillation precisely. To overcome this problem, we employ two different methods, namely ‘reflection measurement’ and ‘drop-port measurement.’ In the former method, the reflection port \((s_{\text{out,}\text{r}})\) is used. From Eq. (4), the reflection is simply proportional to the light energy in the CCW mode. On the other hand, the latter method employs an additional tapered fiber, which is called drop-port tapered fiber. The output power in a drop-port fiber is also proportional to the light energy in the cavity. A clear advantage of this method is that the energy in both the CW and CCW modes can be observed simultaneously. The reflection measurement can be performed with a single tapered fiber, which simplifies the experimental setup. This enables us to obtain data with high stability and accuracy. However, obviously it is difficult to observe the energy in CW modes with a reflection measurement. So, we first employed a reflection measurement to carefully analyze the experimental results and compare them with simulation results. Then, we confirmed that there is indeed an energy oscillation between the two modes by using a drop-port measurement.

3. Experimental results

We fabricated our silica toroid microcavity using (1) photolithography, (2) SiO\(_2\) etching, (3) XeF\(_2\) dry etching and (4) laser reflow [1]. We employed a tapered fiber to couple the light into the microcavity. The fabricated tapered fiber had a transmittance of over 90%. One of the transmission spectra of the fabricated microcavity is shown in the bottom panel of Fig. 2(c). There is clear resonance splitting caused by coupling between the CW and CCW modes. The linewidth of the resonance is 6.3 MHz \((Q_{\text{load}}\ of\ 3 \times 10^7)\) and the splitting is 85 MHz.

Fig. 2 (a) Experimental setup for reflection measurement. (b) Reflected signals from the cavity for different modes. Black (solid), gray (solid) and red (dashed) lines are the reflected signals with and without the cavity and the fitting curve, respectively. The input pulse widths were 10, 8 and 5 ns for the top, middle and bottom panels, respectively. It should be noted that the detected signals were offset by the remaining ASE noise and it was removed from the figure. (c) The transmission spectra of the modes employed in (b).

First, we performed a reflection measurement. Figure 2(a) is a block diagram of the experimental setup. The continuous light output from a tunable laser source (TLS) is turned into rectangular pulses using an electro-optical modulator (EOM). The RF signal driving the EOM is generated by a pulse pattern generator (PPG). The trigger signal is input into an optical sampling oscilloscope (OSO). A polarization controller (PC) is employed to adjust the polarization of the input light. An optical circulator is used to extract reflected light. The reflected light from a microcavity is amplified with an erbium-doped fiber amplifier (EDFA). Finally, the OSO detects and records the reflected light. Figure 2(b) shows the reflected signal from the cavity for different modes (different cavities). As can be seen, the reflected signal oscillates periodically when we input a signal with a rectangular shape. This suggests that there is an energy oscillation between the CW and CCW modes although only a CCW mode (a reflected signal) can be observed with this setup. The oscillation period in each panel is different due to the difference in the coupling rate \(\kappa\). Figure 2(c) shows transmission
spectra that correspond to Fig. 2(b). $\gamma$ and $\kappa$ that can be estimated from the spectra shown in Fig. 2(c) agree well with those calculated from the reflected signals shown in Fig. 2(b). This agreement also suggests that the oscillation in the reflected signal is due to the coupling between the CW and CCW modes.

Finally, we describe experiments based on the drop-port measurement. By using this method, we confirmed that there is indeed an energy oscillation between the two modes. The experimental setup is shown in Fig. 3(a). The energies in the CW and CCW modes are extracted directly from the drop-port tapered fiber, and are then detected with the OSO after amplification. Note that our drop-port tapered fiber is bent and its position is manipulated independently by a nanopositioner. This setup enables us to control the coupling rate between the drop-port tapered fiber and the cavity easily and accurately. Despite being bent, the fabricated tapered fiber has a transmittance of over 80%. Figure 3(b) shows the result of the drop-port measurement. We employed the same modes as in the bottom panel of Figs. 2(b) and 2(c). As seen from the figure, the energy clearly oscillates between the CW and CCW modes. This is direct evidence showing that there is indeed an energy oscillation between the CW and CCW modes. In addition, the oscillation period agrees well with that estimated in Fig. 2(b). Here $\gamma$ is slightly larger than that in Fig. 2(b). This is believed to be due to the additional coupling loss induced by the drop tapered fiber. From the figure, we can conclude that we observed the energy oscillation between counter propagating WGMs. This is the first observation of coupling between modes with an ultra high $Q$ of over [107/10^7?] in the time domain.

4. Conclusion

In conclusion, we have reported the first observation of energy oscillation between two coupled ultra-high $Q$ whispering gallery modes in the time domain. We employed CW and CCW modes in a silica toroid microcavity because they provided a good platform for our experiments. Thanks to the large $\Gamma$, which is due to the large coupling rate between the two modes and an ultra-high $Q$ factor, clear energy oscillation was excited and observed. By using the reflection measurement, we confirmed that the oscillation periods in the time domain were the same as those inferred from the mode splitting in the frequency domain. In addition, we observed the energy oscillation between the CW and CCW modes simultaneously by taking advantage of the drop-port measurement technique. We believe that our results pave the way toward the development of a method for controlling the coupling states between ultra high $Q$ microcavities, which is important in terms of achieving quantum information processing.

References